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ORIGINAL PAPER

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Behavior of temperature-based water stress indicators in BIOTIC-controlled irrigation

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Abstract A subsurface drip irrigation study with cotton used canopy temperature to determine signals for irrigation control during 2002–2004. Timing of irrigation applications was controlled by the biologically identified optimal temperature interactive console (BIOTIC) protocol, which used stress time (ST) and a crop-specific optimum temperature to indicate water stress. ST was the cumulative daily time quantity when cotton canopy temperature exceeded 28°C. STs between 5.5 and 8.5 h in 1 h increments were irrigation signal criteria, which produced different irrigation regimes. This investigation examined the association among ST, daily average canopy temperature (T_c), canopy and air temperature difference (T_c-T_a), and the relative crop water stress index (RCWSI) including their relationship with lint yield. Number of irrigation signals decreased linearly with ST at the rate of −10.2 and −8.7 irrigations per 1 h increase of ST in 2003 and 2004. There were significant curvilinear relationships between ST and the average daily stress on days with irrigation signals and for days without irrigation signals across years. The percentage of positive daily (T_c-T_a) values increased with ST level. ST and T_c were positively related in all irrigation signal treatments with 5.5 and 6.5 h being significant in 2003 and 2004. Yield declined at the rate of 343 kg lint/ha for each 1 h increase of ST for days with irrigation signals. ST, mathematically the most simple of the canopy temperature-based parameters, provided the most consistent estimate of crop water stress and correlation with lint yield. The power of ST to characterize water stress effects on crop productivity evolves from being an integrated value of time while canopy temperature exceeds a physiologically based threshold value.

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Introduction

Plant canopy temperature is a useful measure for identifying crop water status (Tanner 1963; Ehrler et al. 1978). Plants grow in a two-component environment with roots distributed in soil and above ground vegetation exposed to the atmosphere. A plant is an excellent integrator of its two-component environment and provides signals that contain useful crop management information. A real-time indicator of plant water status is provided by midday canopy temperature.

Methods for quantifying the water stress level of crops have been intensively studied because this information can be useful in making crop production management decisions. The earliest symptom of a change in soil water availability in response to an abrupt decrease in irrigation input was a decrease in plant leaf water potential followed by elevated canopy temperature. This occurred within one or two days in cotton when the irrigation regime was modified (Wanjura and Upchurch 2002).

Plant canopy temperature has been used as an indicator of water stress since infrared thermometers (ITs) made it possible to make this measurement without physically contacting the plant (Ehrler et al. 1978). The evolution of using canopy temperature to measure water stress has progressed from once-a-day measurements, to relating temperature to a base temperature, to differences between air temperature and canopy temperature. The crop water stress index (CWSI) description of the atmospheric environment's effect on plant water stress was derived theoretically by Jackson et al. (1981) and empirically by Idso et al. (1981) and Idso (1982). Other discussions on the proper application and procedures for using CWSI have been presented in articles by Jackson et al. (1988) and Gardner et al. (1992). Kacira et al. (2002) reported that CWSI values detected plant water stress 1–2 days prior to visual symptoms in plants in growth chambers. Due to the need to accurately measure many environmental parameters, they expressed the need to reduce the complexity of CWSI to meet practical concerns for field application. Irrigation scheduling possibilities were indicated with corn where mean seasonal CWSI was non-linearly related to grain yield and mean CWSI values >0.22 decreased yield (Irmak et al. 2000).

Viewing plants as integrators of their environment is embodied in the irrigation timing protocol, biologically identified optimal temperature interactive console (BIOTIC; Upchurch et al. 1996), which uses canopy temperature to indicate when a crop is experiencing some level of water stress. The specific amount of time that canopy temperature of a crop exceeds its optimum temperature threshold controls irrigation timing. The resulting cumulative series of irrigations maintains the crop at a controlled water status. Selecting different time threshold values controls plant water status at different levels. The daily accumulation of time above the crop's temperature threshold directly produces the irrigation signal. Thus a specific time threshold can control a sequence of irrigation signals. This produces a series of irrigations that result in an array of canopy temperatures and quantities of time when the plant is above its temperature threshold. The value of the threshold temperature also affects the number of irrigations and the distribution of canopy temperatures as reported by Wanjura and Mahan (1994) where a range of threshold temperatures of 26–32°C were used. In practice the temperature threshold is chosen to closely approximate the optimum temperature of the crop and a time threshold is selected to establish the desired irrigation level. The time threshold used to activate an irrigation signal affects daily stress time (ST) since it and weather conditions control the occurrence of irrigation applications. The objective of this report was to examine the changes in different temperature-based indices while the canopy temperature was above the crop's optimum temperature threshold, and to examine their relationship with cotton yield for different time threshold-controlled irrigation regimes.

Materials and methods

A subsurface drip irrigation system was installed in the Plant Stress and Water Conservation Laboratory field at Lubbock, TX, USA. Irrigation laterals were located under each bed with 1 m spacing between beds. Lateral diameter was 22 mm ID with 0.87 lph emitters, which were located at 0.6 m intervals along the lateral length. Each irrigation zone contained eight rows 165 m long and flow was individually metered. An Elgal-Agro Controller Ver. 109 (Eldar-Shany, Yad Mordechai, 79145, Israel) was activated by a 5 mV signal from a Campbell Scientific CR 7 data logger that calculated ST values and computed irrigation signals based on the average canopy temperature measured by infrared thermocouples in treatments located in replications 2 and 3 in each year.

The time threshold (TT) is a specific quantity of time when canopy temperature exceeds 28°C and is an integral part of the BIOTIC protocol for timing irrigation applications. The selection of different TT values results in variable irrigation amounts causing different crop water status conditions. Air temperature >28°C, canopy temperature >28°C, and net radiation >200 Wm^{-2} were required for a time interval to be added to the daily ST accumulation that determined the occurrence of an irrigation signal. Irrigation signals were dependent on the amount of time above a canopy temperature of 28°C (referred to as ST) exceeding the TT for each irrigation treatment. Irrigation decisions were made daily and a 5 mm application occurred in response to an irrigation signal, which was over-ridden by sufficient rain. The target amount of water application was 5 mm by either rain or irrigation. Rain events >5 mm were accumulated and prevented irrigation until its accumulation was reduced to zero at the rate of 5 mm/day. A 5 mm irrigation was applied in response to the next irrigation signal regardless of the number of days between irrigation signals.

Three irrigation treatments in 2002 were controlled by TTs of 2.5, 5.5, and 7.5 h, which were hypothesized to create conditions of excessive water application, optimum irrigation, and water stress. In 2003 and 2004 irrigation treatments were established using TTs of 5.5, 6.5, 7.5, and 8.5 h. Each year a single plot that only received rain after emergence (DRY) was included as a non-irrigated reference. The cotton variety Paymaster 2326 BGRR was planted on 13 May of each year in north–south rows having a spacing of 1 m between beds. Prior to emergence small irrigations were applied to ensure adequate soil water for seed germination and emergence in all treatments and the DRY plot. Final plant populations averaged 126,000, 119,000, and 126,000 plants/ha, respectively, in 2002, 2003, and 2004.

The studies were arranged in a randomized complete block design with four replications in each year. One infrared thermocouple (Model IRt/c .2 G-K-80F/20C, EXERGEN Corporation)[1] was placed in two replications of each TT treatment and positioned directly above the row at a height to provide a nadir view of the top surface of the cotton canopy. The field-of-view of the IT was 28°. Canopy temperatures were not measured before the squaring growth stage when canopy size became large enough to hide the soil surface while viewing the top of the canopy. The height of the IT was changed, as the cotton canopy size increased, to only view the top canopy surface without viewing bare soil.

[1]Mention of trade names or commercial products in this publication is for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

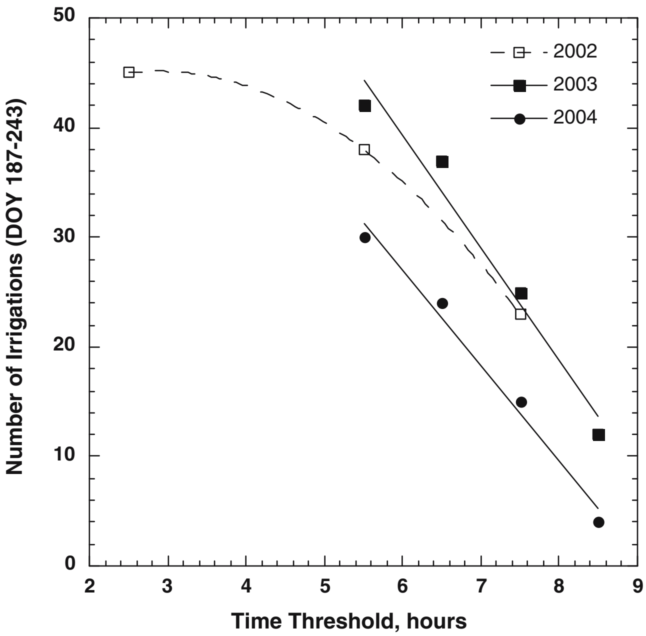

Fig. 1 Number of irrigations applied by multiple time thresholds between DOY 187 and DOY 243 from 2002 to 2004

Air temperature, relative humidity, net radiation, and wind speed were measured 2 m above ground level. All sensors obtained readings at 15 s intervals and 15 min averages were recorded.

Biomass hand-harvests were made periodically during the season to document cotton vegetative growth and crop boll development. Lint yield was determined from hand-harvesting selected areas in all plots and from stripper-harvesting the center four rows of each plot.

Results and discussion

Year 2003 was warmer than 2004 and had a dry soil water profile to begin the growing season in contrast to 2004, which had a full soil water profile at planting and cooler temperatures during the growing season. In-season rain was also higher in 2004 than 2003. Irrigation was applied primarily during July and August. The heat unit (base temperature = 15.6°C) accumulations for these two months were 663, 701, and 560°C-days for 2002, 2003, and 2004, respectively. Heat units (°C-days) are calculated from daily air temperature as: $((Ta_{max} - Ta_{min})/2) - 15.6°C$.

Daily ST values

Time thresholds are predetermined levels of ST used to generate irrigation signals and consequently irrigation regimes for crop production. The TT, in combination with daily weather conditions, determines the daily ST for a crop. The daily accumulation of ST was dependent on canopy temperature exceeding 28°C during the day when air temperature was >28°C and net radiation was >200 Wm^{-2}. All temperature and environmental sensors were interrogated in 15 s intervals and stored as 15 min averages. The ST for multiple TT is given in Table 1 for the 2002–2004 growing seasons. Average daily ST values for the irrigation period from DOY 187 to DOY 243 increased as the magnitude of the TT increased, in each year for all days in the period, as well as for only the days when irrigation signals occurred. ST for days when irrigation signals occurred is shown because these days have higher stress values than all days in the irrigation period, which includes days when canopy temperatures were cool and did not produce irrigation signals.

The STs for all TT treatments were higher in 2003 than 2004, for all days as well as days when irrigation signals occurred. The differences in ST within treatments were relatively stable across TT levels on days with irrigation signals, with values of 0.37, 0.23, 0.25, and 0.12 h for 5.5, 6.5, 7.5, and 8.5 h TT treatments, respectively. The same comparisons for all days of the irrigation period were 1.18, 1.30, 1.49, and 1.47 h. The smaller ST differences between years on days with irrigation signals is due to the consistency of irrigation

Table 1 Average daily stress times (STs) for time threshold treatments and DRY for all days and for days when irrigation signals occurred, DOY 187–243, 2002–2004

Year	Time threshold treatments					
	2.5	5.5	6.5	7.5	8.5	DRY
ST for all days, min (h)[a]						
2002	319 (5.32)	359 (5.98)	–	402 (6.70)	–	454 (7.57)
2003	–	378 (6.30)	398 (6.63)	427 (7.12)	459 (7.65)	492 (8.20)
2004	–	307 (5.12)	320 (5.33)	338 (5.63)	371 (6.18)	363 (6.01)
ST for days with irrigation signals, min (h)[a]						
2002	352 (5.87)	418 (6.97)	–	485 (8.08)	–	–
2003	–	424 (7.07)	447 (7.45)	484 (8.07)	528 (8.80)	–
2004	–	402 (6.70)	433 (7.22)	469 (7.82)	521 (8.68)	–

[a]The daily accumulation of ST was dependent on canopy temperature exceeding 28°C during the day when air temperature was >28°C and net radiation >200 Wm^{-2}

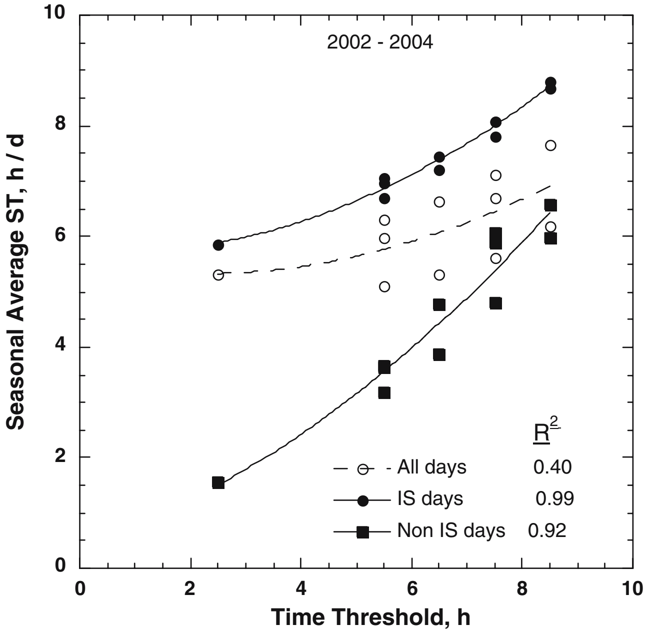

Fig. 2 Time threshold relationships with average seasonal stress time (ST) for three groups of days: (a) all days during the irrigation period, (b) days with irrigation signals, and (c) days without irrigation signals, from DOY 187 to 243 in 2002–2004

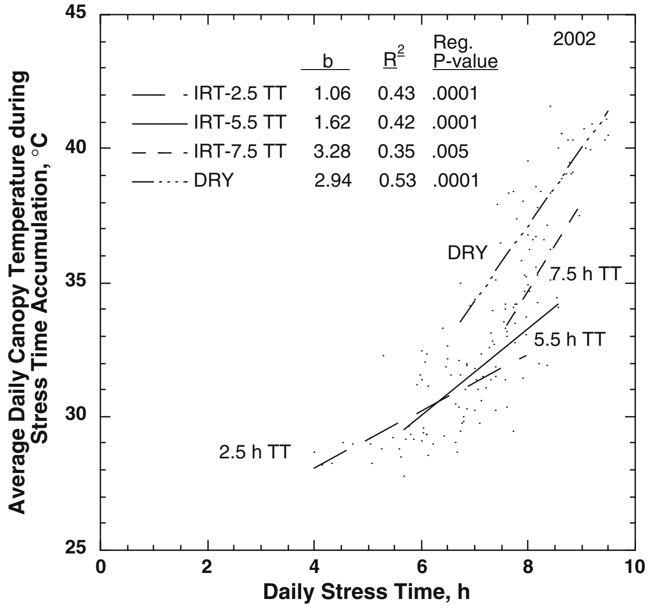

Fig. 3 Relationship of ST and canopy temperature during the period of ST accumulation for time threshold treatments in 2002. The data for each time threshold treatment includes days when irrigation signals occurred. The number of data points was 43, 40, 21, and 40, respectively, for the treatments 2.5, 5.5, 7.5 TT and the DRY reference

control caused by the ST criteria for irrigation signals in the individual treatments. Even though weather conditions were different in the two years, the irrigation ST criteria for each treatment did not change. What did change was the number of irrigation signals and amount of irrigation applied in each year for each TT treatment (Fig. 1).

Time thresholds and irrigation events

Increasing time threshold level reduces the number of irrigation signals and amount of water applied since 5 mm is applied in each irrigation event (Fig. 1). The change in number of irrigation signals between 5.5 and 2.5 h TT in 2002 was lower than the linear trend between 5.5 and 7.5 h TT. The lower increase in number of irrigation signals resulting from the 2.5 h TT is an indication that its water level was higher than required for efficient water use. Consequently in the following two years the 5.5 h TT was used as the lowest TT, and the performance of three higher TT differing in 1 h increments was investigated to evaluate their consistency in producing irrigation signals under the environments for those years.

In 2003 and 2004 time thresholds were linearly related to number of irrigation events between 5.5 and 8.5 h. The slopes of the linear relationships were −10.2 and −8.7 irrigations per 1 h change in TT in 2003 and 2004, respectively. These slopes differ slightly between years due to differences in atmospheric environmental conditions and amount of rain. The number of irrigations for 5.5 and 7.5 h TT in 2002 is similar to the numbers observed for the same TT in 2003. For irrigation scheduling, the linear relationship among TTs in 2003 and 2004 suggests that the soil water level differences among TTs remained consistent across years.

The linear response of number of irrigations with TT from 5.5 to 8.5 h suggests that all water applications were in the deficit irrigation region. The 2.5 h TT in 2002 was probably well watered since its lint yield of 1,588 kg/ha was not significantly different from 1,555 kg/ha produced by the 5.5 h TT.

Time thresholds versus stress time

Time thresholds supply different levels of irrigation to crops by using different amounts of daily ST to provide irrigation signals. The effect that TT exerts on ST is illustrated for all days, days when irrigation signals occurred, and days when irrigation signals were not generated during the irrigation period (Fig. 2). ST was significantly related to TT in each of the day groups. ST increased most rapidly with higher values of TT for the days without irrigation signals followed by the days with irrigation signals and then all days. The coefficient of determination was 0.99 for the second-order polynomial relating TT to ST on days with irrigation signals, 0.92 for days without irrigation signals, and lowest at 0.40 for all days during the irrigation period. The high correlation for days with irrigation signals is a consequence of the consistency of ST control level for the different TT,

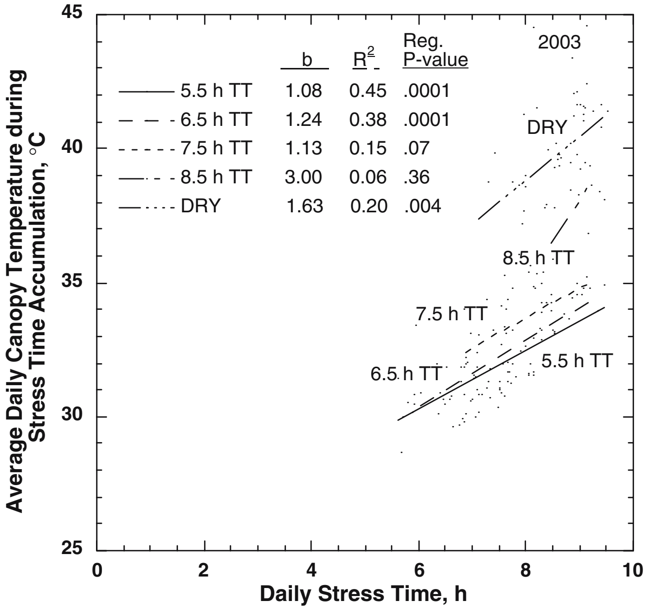

Fig. 4 Relationship of ST and canopy temperature during the period of ST accumulation for time threshold treatments in 2003. The data for each time threshold treatment includes days when irrigation signals occurred. The number of data points was 42, 38, 25, 15, and 42, respectively, for the treatments 5.5, 6.5, 7.5, 8.5 TT, and the DRY reference

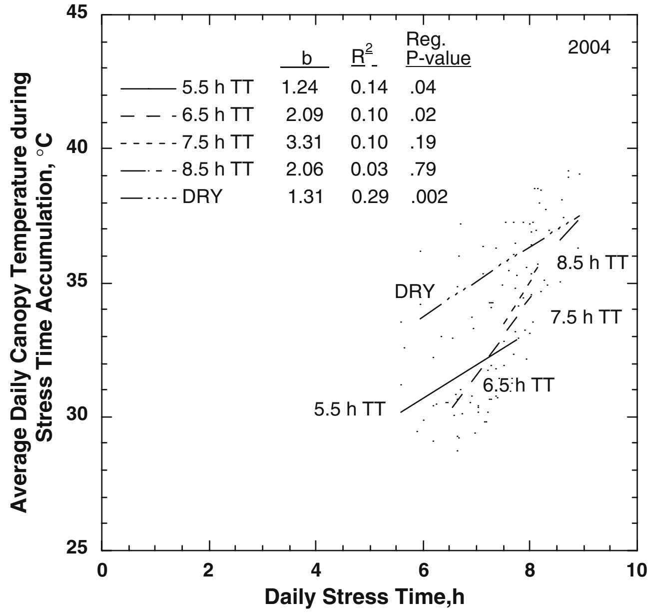

Fig. 5 Relationship of ST and canopy temperature during the period of ST accumulation for time threshold treatments in 2004. The data for each time threshold treatment includes days when irrigation signals occurred. The number of data points was 30, 24, 15, 4, and 30, respectively, for the 5.5, 6.5, 7.5, 8.5 TT, and the DRY reference

which only includes the days that meet or exceed the ST criterion for irrigation signals.

Daily ST versus daily canopy temperature

Daily ST is only accumulated while canopy temperature exceeded 28°C during the day, with air temperature >28°C and net radiation >200 W/m^2. Canopy temperature and ST are linearly related in each year as shown in Figs. 3, 4, and 5. The daily ST–T_c regression lines indicate that temperatures were warmer in 2002 and 2003 than in 2004. The linear regressions for the 2.5 h TT treatment in 2002 and the 5.5 h TT treatment and the DRY reference in each year were significant at the 0.04 probability level or higher. The 7.5 h TT linear regression was significant in 2002 and 2003. The 8.5 h TT treatment linear regression was not significant in 2003 or 2004. The vertical change in the linear regression lines for each TT treatment and the DRY reference represents the range of average daily T_c during the period of ST accumulation. The regressions for the 5.5 h TT and the DRY plot can be compared because their data includes the same days in each year. The slopes (*b* values) of the linear regressions for the DRY plot were greater than for the 5.5 h TT treatment. The combination of higher ST values and less soil water in the DRY plot resulted in higher average daily canopy temperature than the 5.5 h TT treatment.

In 2002, the range in daily canopy temperatures was lowest for the 2.5 h TT treatment and increased for the 5.5 and 7.5 h TT. The 2.5 h TT treatment had the largest range in ST, which progressively declined for the 5.5 h TT and then the 7.5 h TT. The responses of canopy temperature and ST resulted in canopy temperature change per 1 h change in ST being highest in the 7.5 h TT treatment followed by decreasing responses for the 5.5 h and 2.5 h TT.

The change of daily canopy temperature in relation to ST for the 5.5, 6.5, and 7.5 h TT treatments in 2003 (Fig. 4) were similar as indicated by the linear slope values. The 8.5 h TT had the highest change in daily canopy temperature in relation to ST among the TT treatments. The DRY plot had the highest canopy temperatures that were caused by not being irrigated and low rain. The daily ST and canopy temperature of the DRY plot was higher in 2003 than 2002. The DRY plot was reflecting the natural water stress difference between the two years.

The change of canopy temperature in relation to daily ST in 2004 for 5.5 h TT was lower than in the previous two years. The regression *P* values for the 7.5 and 8.5 h TT treatments for the relationships of daily ST with daily canopy temperature were too low to permit comparisons between 2003 and 2004.

Daily ST versus daily (T_c–T_a)

Daily ST is an accumulated time value when T_c>28°C, ignoring the actual canopy temperature values. The difference between canopy temperature

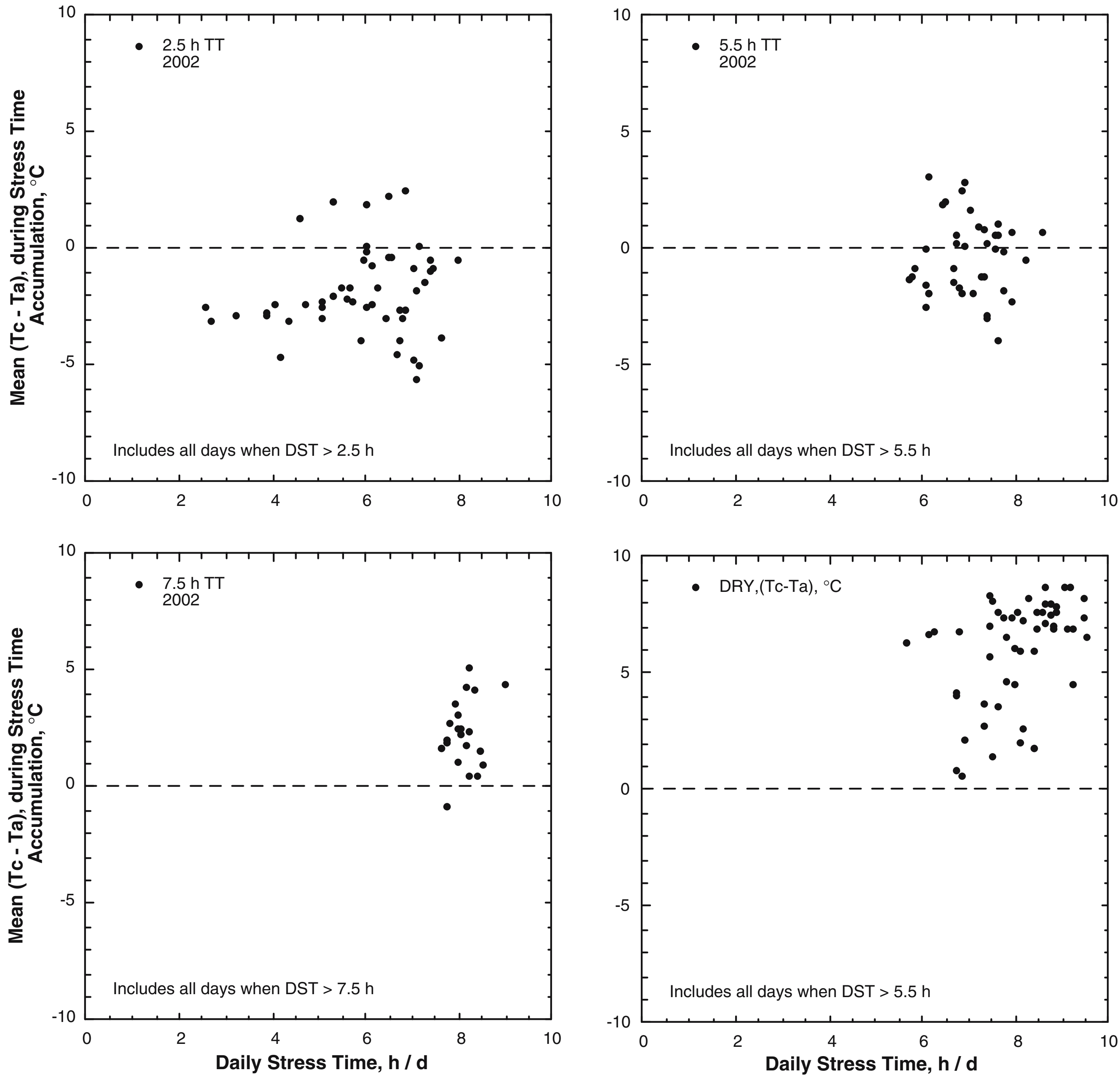

Fig. 6 Relationship of daily ST with (T_c-T_a) on days when irrigation signals occurred for three time threshold treatments and DRY, 2002

(T_c) and air temperature at 2 m (T_a) is an indicator of water stress because the crop canopy, under non-limited water condition, transpires and cools itself. For the TT treatments in 2002, the relationship of daily ST values with (T_c-T_a) values for the days when irrigation signals occurred in each time threshold is shown in Fig. 6. A pattern of increasing number of positive (T_c-T_a) values compared to negative (T_c-T_a) values is indicated as the time thresholds increase from 2.5 to 7.5 h and the DRY plot. This pattern is consistent with Fig. 2 where daily ST increases with TT values that determine irrigation signals and irrigation application. ST averages for the days when irrigation signals occurred were 5.9, 7.0, and 8.1 for the 2.5, 5.5, and 7.5 h time thresholds (Table 1).

During 2003, daily ST did not have functional relationships with daily mean (T_c-T_a) in any of the time threshold treatments (Fig. 7). However, the pattern of increasing portion of positive (T_c-T_a) values as time threshold levels increased was evident and similar to 2002. The effectiveness of irrigation control by the different time threshold treatments in maintaining lower cotton water stress levels can be seen by comparing the proportion of positive and negative (T_c-T_a) values to those in the DRY plot. The average ST for the days when irrigation signals occurred were 7.1, 7.5, 8.1, and

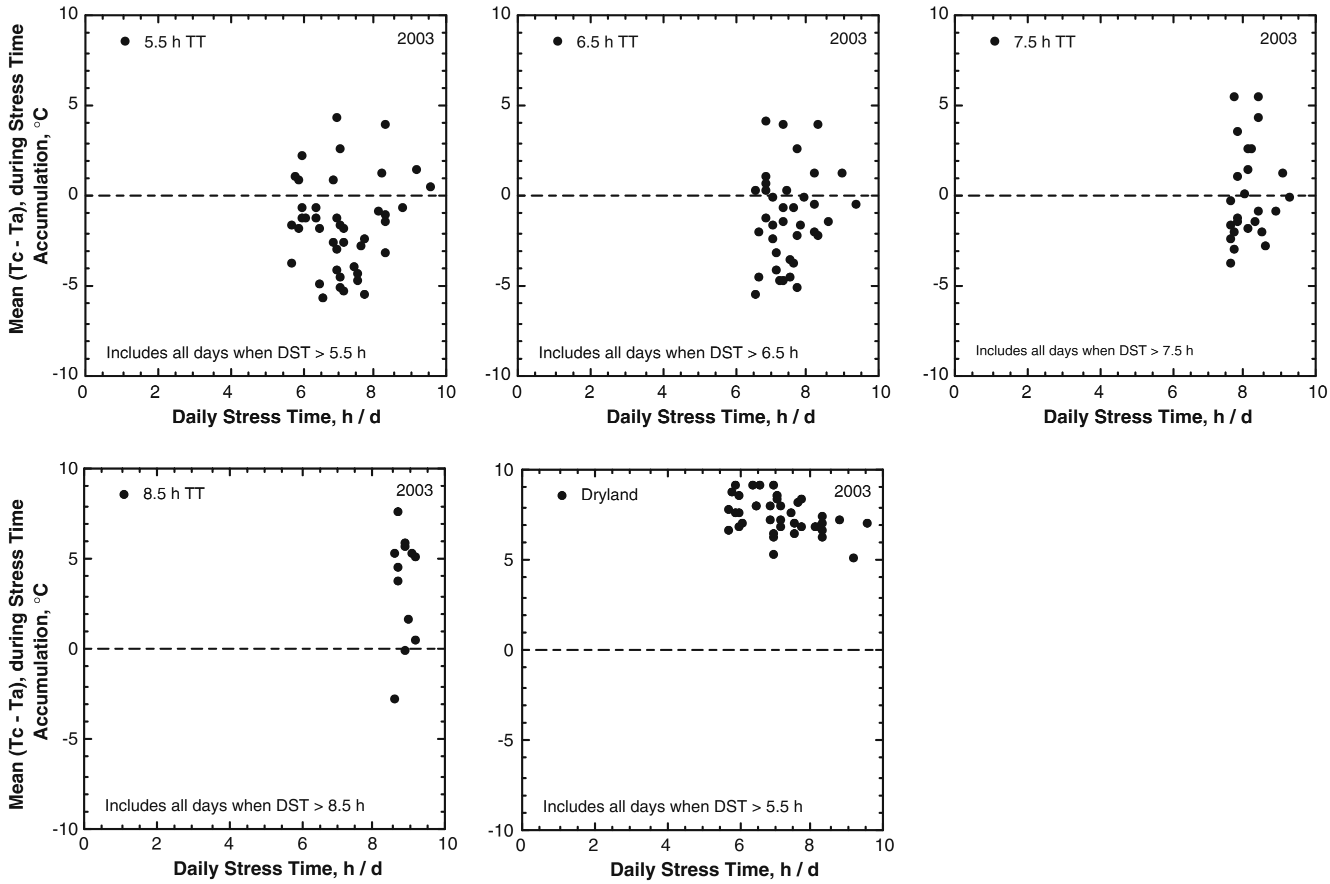

Fig. 7 Relationship of daily ST with ($T_c - T_a$) on days when irrigation signals occurred for four time threshold treatments and DRY, 2003

8.8 h for 5.5, 6.5, 7.5, and 8.5 h time thresholds, respectively (Table 1).

The pattern of an increasing proportion of positive to negative ($T_c - T_a$) values as the time threshold level increased was again present in 2004 for days when irrigation signals occurred (Fig. 8). The number of irrigation signals was lower than in previous years due to a higher level of soil water at the beginning as well as more rain during the growing season. There were also fewer days in the data set due to no stress accumulation (time when $T_c > 28°C$) from DOY 206 through DOY 209 in any treatment due to cool cloudy conditions. (There was also no data for DOY 223 and DOY 224 due to data logger damage that occurred from lightning during a thunderstorm). Average ST for the days when irrigation signals occurred was 6.7, 7.2, 7.8, and 8.7 h for 5.5, 6.5, 7.5, and 8.5 h time thresholds, respectively (Table 1).

The range (scatter) of daily ST decreased in all years as the TT value increased. The scatter of daily ST shown for the DRY plot was comparable to that of the 5.5 h TT since the same TT value was used to select days for comparison with the irrigated treatments.

Table 2 Average daily canopy temperature during ST accumulation for time threshold treatments and DRY, DOY 187–243, 2002–2004

Year	Time thresholds, h					
	2.5	5.5	6.5	7.5	8.5	DRY
2002	29.7°C	30.7°C	–	32.7°C	–	36.5°C
2003	–	30.8°C	31.4°C	32.9°C	35.5°C	38.9°C
2004	–	30.4°C	30.7°C	32.1°C	33.4°C	33.7°C

Relative crop water stress index (RCWSI)

Daily values of RCWSI in 2002 were calculated using canopy temperatures of the 5.5 h TT treatment as an approximation of low water stress and the DRY plot as a high water stress condition. RCWSI $= (T_{ci} - T_{c5.5\text{ h TT}})/(T_{cDRY} - T_{c5.5\text{ h TT}})$ was used to compute RCWSI, where T_{ci} were canopy temperatures for 2.5, 6.5, 7.5 and 8.5 h TT treatments. During the period from DOY 187 through DOY 243, the 7.5 h TT treatment was consistently higher and the 2.5 h TT treatment had lower water stress than the 5.5 h TT treatment (Fig. 9a). For the entire period RCWSI averaged 0.34 and −0.16, respectively, for the 7.5 and 2.5 h TT treatments.

The RCWSI values in 2003 for 6.5, 7.5, and 8.5 h TT were not greater than that for 5.5 h TT until DOY 195

Table 3 Linear regression statistics for ST, canopy temperature (T_c), canopy minus air temperature (T_c-T_a), and relative crop water stress index (RCWSI) during the period of ST accumulation on days when irrigation signals occurred and lint yield, 2003–2004

Years	Intercept	Slope	R^2 value	Regression P value
Stress time, h/day				
2003–2004	3,697	−347.1	0.82	0.002
2003	3,566	−343.7	0.97	0.02
2004	3,469	−303.5	0.94	0.03
Canopy temperature, °C				
2003–2004	4,064	−90.3	0.60	0.02
2003	3,651	−82.2	0.83	0.09
2004	4,573	−100.9	0.86	0.08
Canopy minus air temperature, °C				
2003–2004	1,088	−75.2	0.24	0.22
2003	900	−119.9	0.89	0.06
2004	1,410	−147.6	0.81	0.10
RCWSI				
2003–2004	985	−184.6	0.06	0.64
2003	980	−795.9	0.79	0.30
2004	1,290	−445.0	0.81	0.29

(Fig. 9b). Afterwards RCWSI for 8.5 h TT increased rapidly and remained highest for the remainder of the period. The RCWSI for 7.5 h TT increased to 0.63 on DOY 229 due to several days without irrigation and then decreased in response to four consecutive days of irrigation. For the entire period RCWSI values averaged 0.07, 0.24, and 0.54 referenced to the 5.5 h TT time threshold in the 6.5, 7.5, and 8.5 h TT treatments.

The RCWSI values in 2004 were generally related to time threshold level (Fig. 9c). There were several periods, i.e., DOY 205–213 and DOY 220–229 when cool temperatures or rain prevented the occurrence of irri-

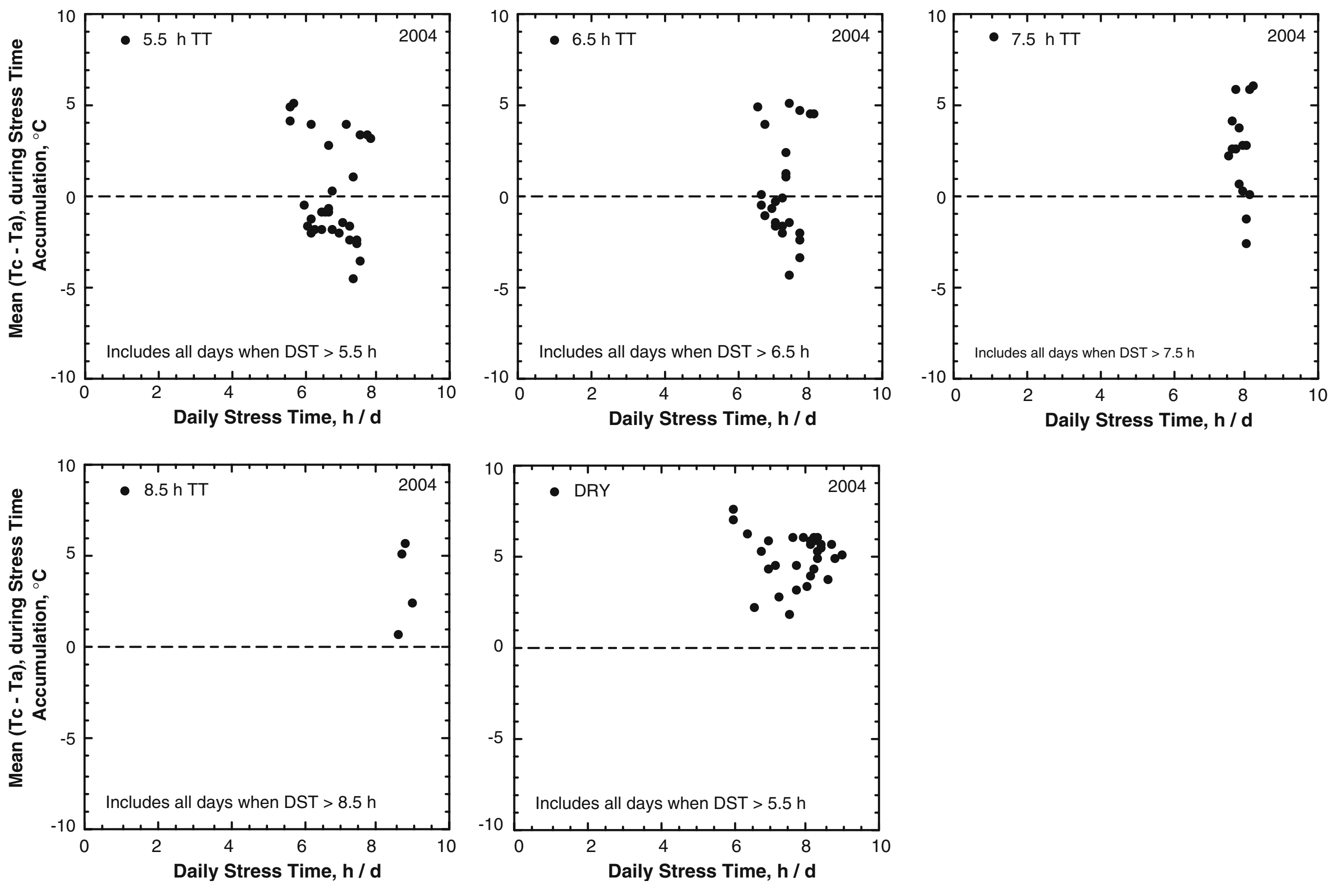

Fig. 8 Relationship of daily ST with (T_c-T_a) on days when irrigation signals occurred for four time threshold treatments and DRY, 2004

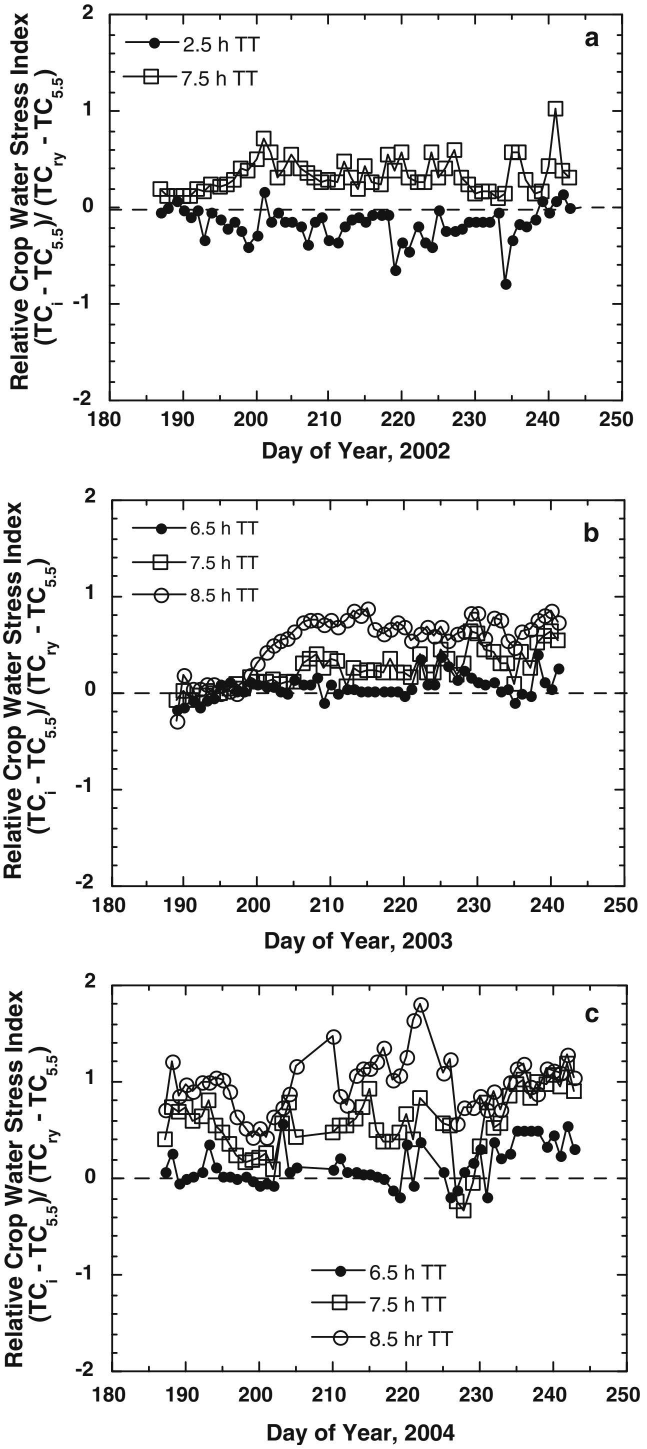

Fig. 9 Relative crop water stress index (RCWSI) values for time threshold treatments, 2002–2004

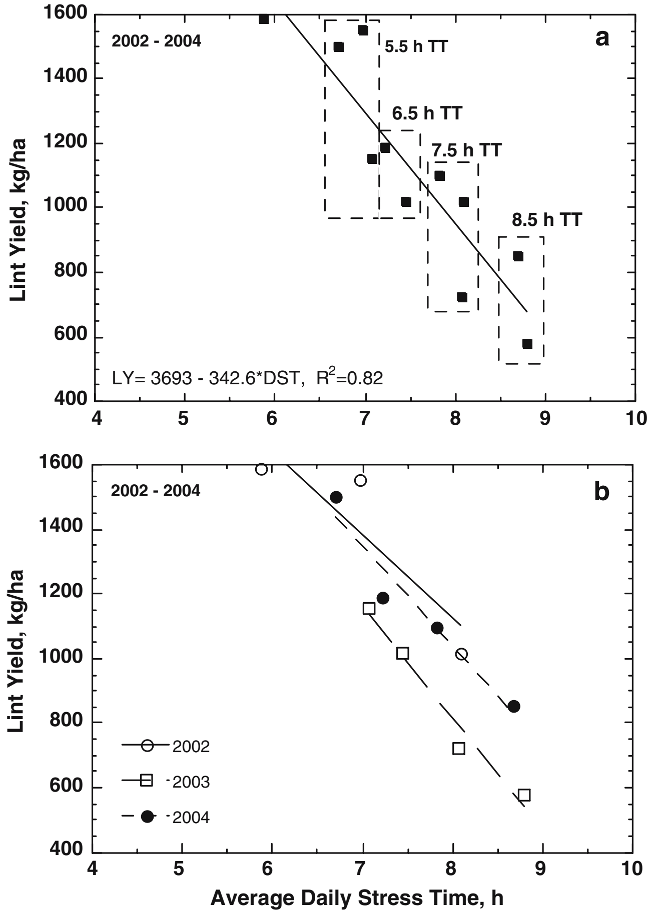

Fig. 10 The common relationships between average daily ST with lint yield for the combined three years, with the responses for each time threshold treatment identified, are shown in (**a**). The individual year relationships between ST and lint yield are given in (**b**). Average daily ST includes only days when irrigation signals occurred during the irrigation period each year

gation signals. During these two periods RCWSI was different among TTs. For the entire period RCWSI averaged 0.15, 0.58, and 0.98 for 6.5, 7.5, and 8.5 h TT treatments relative to the 5.5 h TT.

The RCWSI values were higher for all TT in 2004 than 2003. As shown in Table 2 the average canopy temperatures for TT 6.5, 7.5, 8.5 h, and the Dry plot had larger changes than for the 5.5 h TT treatment, which remained relatively constant during the three years. Thus any inter-year changes in RCWSI for specific TT was attributable to canopy temperature changes in each TT and the DRY plot. The RCWSI increased at the rate of 0.24 and 0.42 units of RCWSI per 1 h increase of TT in 2003 and 2004, respectively.

Yield correlations

Daily ST, T_c, $(T_c - T_a)$, and RCWSI with irrigation signals for days during the irrigation period from DOY 187 to DOY 243 were each correlated with lint yield during 2003 and 2004 (Table 3). Canopy temperature and $(T_c - T_a)$ were related to lint yield within years with regression P values < 0.10 with P values for RCWSI and lint yield being < 0.30. Daily ST had the most significant regression P values for the two individual years and the combined years of 2003 and 2004.

The daily ST–yield relationships for 2002–2004 and for the three individual years are shown in Fig. 10a and b. An average decline of 343 kg lint/ha was estimated for each 1 h increase of ST for irrigation signal days during the irrigation period for the combined three years. The sets of dotted-line boxes group the average daily ST by TT treatment. These groupings illustrate the consistency of ST for the same TT treatments across years. The variation in lint yield within the same TT box is the effect of all other yearly growing season factors on yield. These ST values were lower for all TT treatments in 2004 than 2003. The linear regressions in Fig. 10b show the response of yield within years to the range of TT and the corresponding amounts of irrigation applied. The ST versus lint yield relationships show that the yield response to ST was linear with similar slopes in 2003 and 2004. The ST versus lint yield responses in Fig. 10b and the TT versus number of irrigations in Fig. 1 indicate that amount of irrigation, ST, and yield were closely linked.

Summary

The behavior of selected temperature-based indices for indicating water stress were analyzed from data collected from a subsurface drip irrigation study conducted for 3 years (2002–2004) with cotton in Lubbock, TX, USA. The timing of irrigation applications was determined from continuously measured canopy temperature and specific values of ST referred to as time thresholds (TT).

Time thresholds between 5.5 and 8.5 h were linearly related to number of irrigation events in 2003 and 2004 (Fig. 1). The coefficient of determination was 0.99 for the second-order polynomial relating TT to ST on days with irrigation signals, 0.92 for days without irrigation signals, and (lowest) 0.40 for all days during the irrigation period (Fig. 2). The high correlation for days with irrigation signals was a consequence of ST control level for the different TT, which only included days that satisfied the ST criterion for an irrigation signal.

Daily canopy temperature was positively related with ST but varied among years presumably due to differences in environmental conditions. The percentage of positive ($T_c - T_a$) values, which was an indication of water stress, increased as TT level increased in all years. During the irrigation period the rate of RCWSI increase relative to the 5.5 h TT treatment per 1 h increase in TT value was 0.24 and 0.42 in 2003 and 2004. Daily ST had a single common relationship with lint yield for all years. An average decline of 343 kg lint/ha was estimated for each 1 h increase of ST for days with irrigation signals during the irrigation period.

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